Glass Breakage and Injury - Yet Another New Model?

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Abstract

Today, many quite sophisticated models exist for the calculation of glass breakage due to air blast loading and subsequent effects on persons within reach of the flying glass shards. Further, experience from accidents shows that the lethality rate from flying glass is rather low. Therefore, one might ask the question why do we need an additional new model and what shall it be used for?

Despite the fact that the lethality rate due to flying glass shards is comparatively low, a literature review showed that glass breakage is often the most far-reaching explosion effect and sometimes is responsible for the largest number of injured persons. This is especially true in case of explosions in urban areas due to accidents during the transport of ammunition or due to terrorist attacks like the one at Oklahoma City.

In addition, the review showed that most of the existing glass breakage and lethality/injury models need too many input parameters which are usually not at hand. As an example, beside the size of the window also the thickness of the glass panes is often needed as a main calculation parameter. However, how do we know about the thickness of a glass pane in an existing window in a house before the accident happens destroying this window?

These are some of the reasons why an easily applicable tool for standard quantitative risk analysis purposes, based on a few easily gatherable parameters, was developed in Switzerland. This paper describes the new generic model for glass breakage and lethality/injury due to flying glass. Further, it is imagined that this tool also will help to develop emergency maps and plans, and support rescue forces when it comes to cordon off endangered areas.

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14. ABSTRACT
Today, many quite sophisticated models exist for the calculation of glass breakage due to air blast loading and subsequent effects on persons within reach of the flying glass shards. Fur-ther, experience from accidents shows that the lethality rate from flying glass is rather low. Therefore, one might ask the question why do we need an additional new model and what shall it be used for? Despite the fact that the lethality rate due to flying glass shards is comparatively low, a litera-ture review showed that glass breakage is often the most far-reaching explosion effect and sometimes is responsible for the largest number of injured persons. This is especially true in case of explosions in urban areas due to accidents during the transport of ammunition or due to terrorist attacks like the one at Oklahoma City. In addition, the review showed that most of the existing glass breakage and lethality/injury models need too many input parameters which are usually not at hand. As an example, beside the size of the window also the thickness of the glass panes is often needed as a main calcula-tion parameter. However, how do we know about the thickness of a glass pane in an existing window in a house before the accident happens destroying this window? These are some of the reasons why an easily applicable tool for standard quantitative risk analysis purposes, based on a few easily gatherable parameters, was developed in Switzer-land. This paper describes the new generic model for glass breakage and lethality/injury due to flying glass. Further, it is imagined that this tool also will help to develop emergency maps and plans, and support rescue forces when it comes to cordon off endangered areas.

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1   Introduction

Glass breakage due to air blast loading from accidental explosions has been a major topic at DDESB seminars as long as one can remember. As a consequence quite many sophisticated models, not only for glass breakage but also for subsequent effects on persons within reach of the flying glass shards, were developed over the years.

Figure 1 shows such a state-of-the-art model [1]. This model allows a detailed, physics-based analysis of the vulnerability of room occupants exposed to flying glass and structural debris. Many parameters like:

- type of window
- thickness of glass panes
- furniture in the room shielding an occupant
- position of the occupant relative to the window

and several other things can be taken into account.

On the other hand experience from accidents shows that the lethality rate of room occupants due to flying glass is rather low compared to other explosion effects. Therefore, one might ask the question why do we need another new model and what shall it be used for?

This paper outlines the reasons for developing a new additional glass breakage model, gives some information about how it was developed and explains the model in detail.
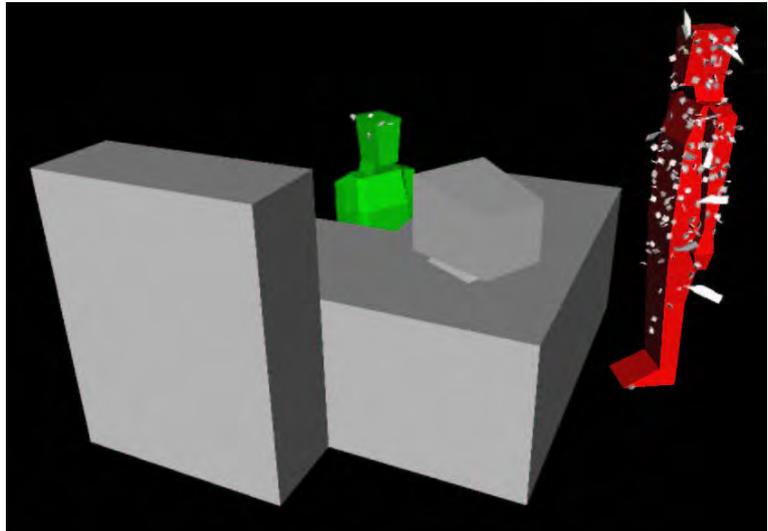
Figure 1: Glass breakage model in the HuLC Code

2   Reasons for Developing a new Model

Switzerland is currently revising and up-dating its safety regulation for the storage of military ammunition and explosives (TLM 75 / Part 2 [2]). This regulation contains a quantitative risk based concept for the safety assessment of such storages. In the risk analysis part of the proc-

ess, until today, only the number of fatally injured people is calculated and used as the representative measure for the hazard of an operation.

When the development of a new glass breakage and lethality/ injury model for implementation in TLM 75 was proposed, questions arose like:

- why do we need a glass injury model?
- why do we even need a separate lethality model for flying glass?
- why is it necessary to develop a new model?

The following intensive discussions and a review of accident data and literature showed a few very important things:

- The lethality rate due to flying glass is rather low, however, the injury rate is very high and often causes the largest number of injured people. Typical examples supporting this statement are the Oklahoma City terrorist bombing in 1995 and the terrorist attack in Dhahran / Saudi Arabia in 1996 [3, 4]. In both cases substantially more than 50 % of the injuries were attributed to flying glass.

- Glass breakage is often the most far reaching explosion effect.

- Glass breakage can cause extensive damage to properties and financial loss. Typical examples are the terrorist attacks in London in the 90ies (Figure 2) [5].

- And finally, glass breakage can be a major threat to important and sensitive buildings like hospitals and government buildings.

All these statements come especially true when explosions in urban areas are due to accidents during the transport of ammunition and explosives or due to terrorist attacks.

Concerning existing glass breakage and injury models it was found that:

- Already many models for breakage as well for injury exist. However, most of these models need (too)

Figure 2: Typical damage to windows in an office building due to air blast

many input parameters which are often not at hand and can, if at all, not be discovered in time when they are needed. As an example, beside the size of the window also the thickness of the glass pane is often needed as a main calculation parameter. However, how do we know about the thickness of a glass pane in an existing window in a house before the accident happens destroying this window?

- Many glass breakage and injury models do not cover the impulse range, but only the pressure rang of a blast load.

- In addition, the range of application of most models is not well defined

- And last but not least, most of the models do not fit with the window and building types common in Switzerland.

Based on this reasoning, it was finally decided to develop an easy-to-use glass breakage and injury model for risk analyses purposes. It was also recognised that, even if injuries will not be taken into account in the standard risk calculation, in many situations additional information about the maximum range of explosion effects will be very important when it comes e.g. to emergency planning.

3 The new Glass Breakage Model

3.1 Development

The new glass breakage and injury model was, of course, not developed completely from scratch. It bases on more than 100 documents like e.g. [6, 7, 8]. These documents and the models described therein were studied, their limitations explored and the "essence" taken out. Additional calculations and comparisons with accident data were made. Expert opinion was used as well in areas with missing data.

As the intention was to develop an easy-to-use model, and given the time frame and financial resources to develop it, it was obvious to come up with an empirical model in the end.

3.2 Basic Assumptions

This section describes the main assumptions made for the development of the model:

- The glass breakage and injury model due to air blast loading shall be a function of the air blast over pressure and the impulse and the result shall be presented in form of P - I diagrams.

- Three window sizes typical for Swiss buildings shall be considered.

Window Size	Glass Area	Used in Building Type
small	< 1 m^2	normal house
medium	1 - 3 m^2	office building, normal house
large	> 3 m^2	shop window, office building

Table 1:Definition of window sizes

- Window data:

  - pane thickness 4 - 6 mm
  - dual pane
  - normal glass (not laminated or specially hardened)
  - modern window, less than 30 to 40 years old

3.3   Window Breakage Probabilities

The following figures illustrate the final results. Figure 3 shows probabilities of glass breakage for "small" windows as a function of pressure and impulse. The probabilities, in the pressure range as well as in the impulse range, are normal distributed (Gauss distribution). The curves itself are hyperbolas.

Generic form of the curves:

(P - A) * (I - B) = C

were:

$$C \quad = \quad e^{(1.3 + 2.23 * \ln(A))}$$ (for all P-I Diagrams)

P, A = pressure values   [kPa]

I, B = impulse values   [kPa-ms resp. Pa-s]
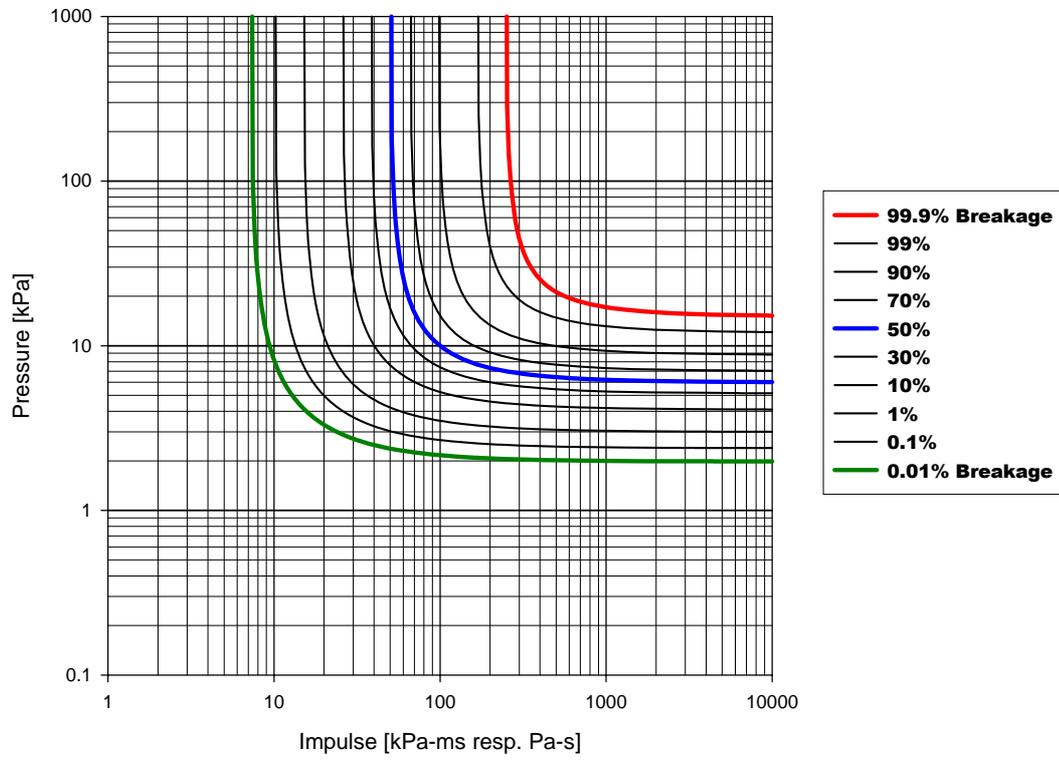
Figure 3: Glass breakage probabilities for "small" windows

P and I are the pressure and impulse values actually loading a window. Therefore, in case a window is loaded face on, for P and I reflected values have to be used. C gives the curvature of the hyperbolas. A and B are defined by probit functions for each window type (Table 2)

Window Size	Function	Remarks
Small	Pr = -1.013 + 3.356 * ln (A) Pr = -2.558 + 1.932 * ln (B)	Pressure Range Impulse Range
Medium	Pr = 0.796 + 3.356 * ln (A) Pr = -0.788 + 1.932 * ln (B)	Pressure Range Impulse Range
Large	Pr = 2.674 + 3.356 * ln (A) Pr = 0.983 + 1.932 * ln (B)	Pressure Range Impulse Range

Table 2: Probit functions for glass breakage

Breakage probability curves for the three defined window types can be calculated with this set of formulas. For the calculation of the actual probability of window breakage given a pressure and an impulse, iteration between the curves is necessary as no closed formula exists.

3.4 Injury Probabilities due to Glass Breakage

Injury probability P-I diagrams for persons staying in the hazardous area behind a window were developed in the same way as for glass breakage for the following three different injury levels:

- minor injury
- severe injury
- fatal injury (fatality)

Minor injuries in this model are injuries which do not lead to permanent disability and which do not require hospitalisation for more than 3 days. This correlates to a level of 1 to 2-3 on the Abbreviated Injury Scale (AIS). Fatal injury probabilities include short and long term fatalities (AIS level 6). Further, the model assumes that medical care is available within reasonable time (usually less than 30 minutes).

Figure 4 and 5 show P-I diagrams for minor injury and fatality for "small" windows. The respective probit functions for all window sizes are given in the Annex and [9]. Further, the probabilities given in these diagrams indicate that a person suffers at least the indicated damage. Therefore, as an example, when calculating the real number of serious injuries the number of fatalities have to be subtracted.

It is obvious that a link exists between the breakage probability of a window and the injury level of people staying in the hazardous area. However, the connection is not linear. Table 3 shows the relationship for different glass breakage levels. As can be seen, for a glass breakage level of 100% the minor injury rate is also 100% and the expected lethality rate is 1%. For a glass breakage level of 1%, however, the minor injury and lethality rate are a factor of 10 lower. This is mainly due to the different velocities of the glass shards at different glass breakage levels. In areas where 100% glass breakage has to be expected the air blast pressure or impulse is usually also very high and therefore leads to a high velocity of the glass shards. In areas with a glass breakage level of 1% the expected velocities of glass shards are lower.

3.5 Comparison with other Models and Limitations

The model presented above was, of course, compared with other existing models and accident data. In general, the new model shows a reasonably good agreement, even though a sound comparison of the models was not very easy to accomplish.
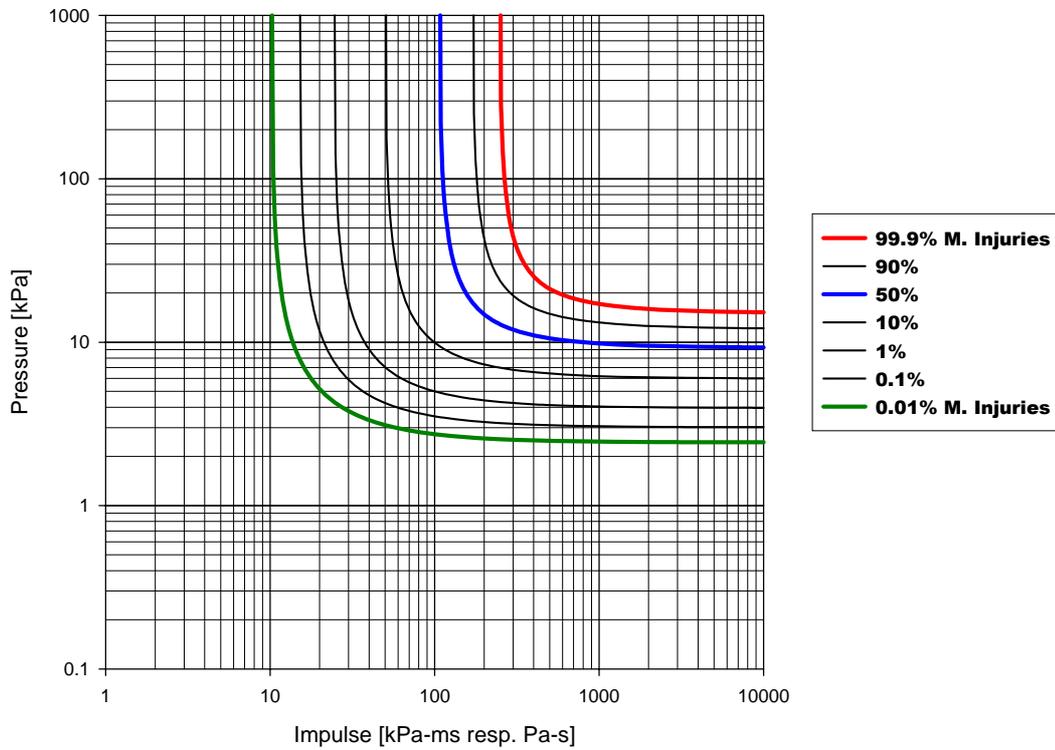
Figure 4: Probability of minor injury for "small" windows
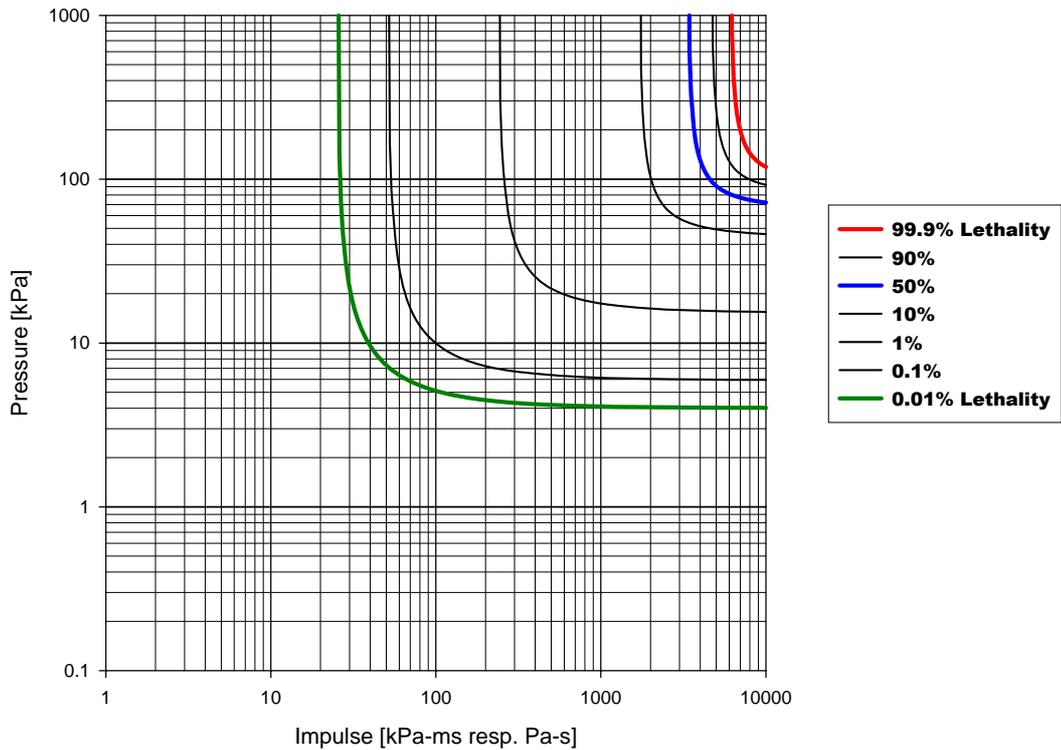
Figure 5: Probability of lethality for "small" windows

Breakage	Minor Injury	Severe Injury	Lethality
100 %	100 %	10 %	1 %
50 %	10 %	1 %	0.1 %
1 %	0.1 %	0.01 %	0.001 %

Table 3: Comparison of glass breakage and injury levels

Figure 6 shows an attempt to compare the new model with existing ones as documented e.g. in the NATO manual AASTP-4 [6] for a charge size (NEW) of 1000 kg. Although the figure indicates consistency between the models, a fair and realistic comparison is in fact not easily possible as the different models shown in the picture are based on partly very different assumptions. As an example, some of the models give average probabilities for all windows in a building where others take the orientation of the building concerning the PES (Potential Explosion Site) into account. Some models do distinguish between different window sizes, others do not.
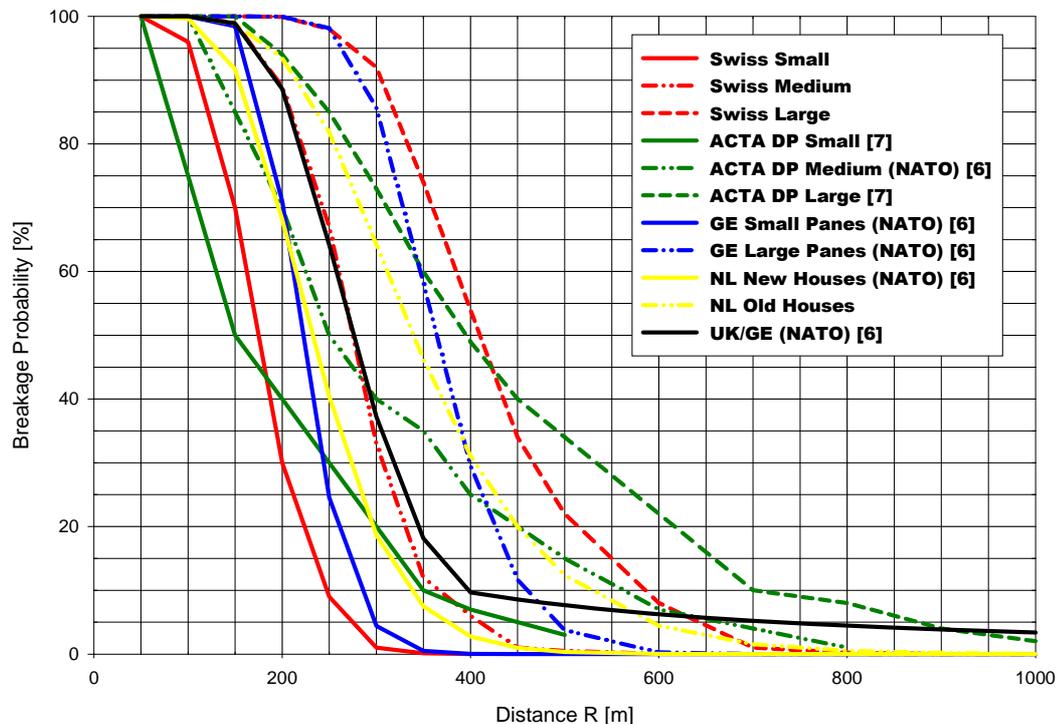
Figure 6: Comparison of different glass breakage models for a charge size of 1 t

Zone1   red: all broken
Zone 2   green: many broken
Zone 3   yellow: few broken
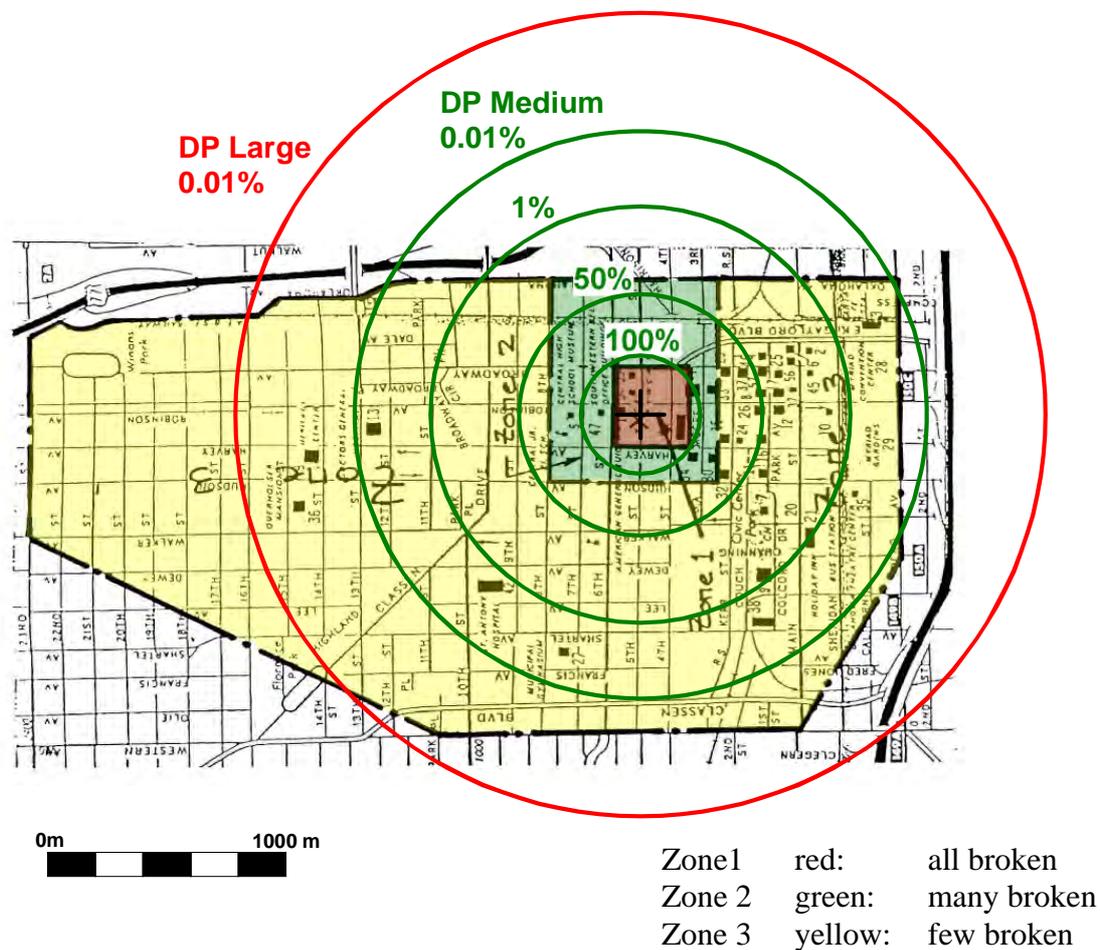
Figure 7: Comparison of the new model with the Oklahoma City incident

A more realistic comparison can be made with accident data. Figure 7 shows a comparison of the Oklahoma City incident data with the new model. The circles show breakage probabilities for face on loaded windows, assuming a charge size of 1500 kg. Despite the fact that agreement is reasonably good, the picture also shows the general limitations of such models:

- Glass breakage depends on so many different parameters that within reasonable financial limits for "normal" risk analyses purposes, it will never be possible to take them all into account. Therefore, an uncertainty being not too small has to be accepted.

- Glass breakage distances also strongly depend on the air blast propagation. Especially in urban areas it is often difficult to predict the "real" pressure acting on windows taking into account all local influences and reflections. This can also be seen in Figure 7 where the air blast propagation to the right was hindered due to the shielding effect of the Murrah building.

- Finally, the same also applies for the injury models. Data for this part is relatively sparse. Therefore, uncertainties are expected to be larger than for the breakage probability. Having the intend use in mind, the injury models presented above are expected to give upper limits rather than "real" average values.

4 Additional Comments for Application

4.1 Intended Use of the Model

The model presented in this paper - first and most important - is **not** to be used as an instrument for designing windows against explosion effects. However, it can be used and will deliver reliable results for the following applications:

- Standard risk analyses for:
  - ammunition and explosives storages
  - ammunition and explosives transport
  - fabrication areas
  - etc.

- Development of emergency plans

- Helps the emergency and rescue forces when it comes to cordon off and evacuate endangered areas, especially in case of transport accidents in urban areas.

4.2 Definition of the Hazardous Area

The injury probabilities given by the model are average values for the hazardous area behind a window, as defined below:

- maximum distance from window: room depth, usually up to approx. 5 to 7 m
- width: width of window plus an angle of 10° to either side of the window

Therefore, to get an average injury probability for persons staying in a building, the total glass area and the layout of the rooms typical for the type of building have to be considered.

4.3   Additional Assumptions

- For windows at the back of a building the calculated probability shall be divided by two (sometimes corner effects may lead to an underpressure instead of an overpressure). Further, an additional air blast pressure reduction may be taken into account.

- The model does not take into account curtains behind a window or shutters in front of it (such devices always can, and tend to be, not in place when they would be helpful !)

- The injury probability is an average value applicable to standing, sitting and lying persons in the hazardous area. Furniture in a room is not taken into account as shielding material.

5   Final Remarks

Based on the latest developments, tests, and accident investigations in this field, a new, easy to use, generic probabilistic model for glass breakage and injuries was developed. The model is intended to be used mainly for standard risk analyses in Switzerland.

The model only needs three easily gatherable input parameters, namely:

- air blast pressure
- air blast impulse
- size of the window (choice out of 3 standard sizes)

The output of the model are probabilities for glass breakage and injury for room occupants staying behind a window in the hazardous area.

Taking into account the general uncertainty of such a prediction model and the inherent variability of many of the mechanism (breaking-up of a window in single glass shards) the model showed good agreement with accident and test data for the window types defined above.

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I 150-28 / 1. Dezember 2003

Annex - Probit Functions

- **General**

In general, a standard normal distribution can be translated to a probit function (and vice versa). The relationship is as follows:

$$\Phi(z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z} e^{\frac{-1}{2}x^2} \cdot dx$$

where:

Φz = probability
assuming: mean value = 0
variants = 1

z = deviation
z = 1 = standard deviation σ
Pr = z + 5

Pr = Probit

These relations are shown in the figure below.

| Likelihood Φ(Pr-5) | 0 | 3E-5 | 1.4E-3 | 2.3E-2 | .16 | .50 | .84 | .977 | .9986 | .9999 | 1 |

- **Probit functions for glass breakage and injury**

Window Size	Function	Remarks
Small	$Pr = -1.013 + 3.356 * \ln(A)$ $Pr = -2.558 + 1.932 * \ln(B)$	Pressure Range Impuls Range
Medium	$Pr = 0.796 + 3.356 * \ln(A)$ $Pr = -0.788 + 1.932 * \ln(B)$	Pressure Range Impuls Range
Large	$Pr = 2.674 + 3.356 * \ln(A)$ $Pr = 0.983 + 1.932 * \ln(B)$	Pressure Range Impuls Range

Table A-1:   Glass Breakage

Window Size	Function	Remarks
Small	$Pr = \exp(1.2855+0.01425*A^{1.5}-6.484/A^{2})$ $Pr = \exp(1.410+0.002949*B-12.154/B)$	Pressure Range Impuls Range
Medium	$Pr = \exp(1.5515+0.008064*A^{2}-2.1878/A^{1.5})$ $Pr = \exp(1.404+0.007422*B-4.798/B)$	Pressure Range Impuls Range
Large	$Pr = \exp(1.5566+0.02456*A^{2}-0.9554/A^{1.5})$ $Pr = \exp(1.404+0.01856*B-1.919/B)$	Pressure Range Impuls Range

Table A-2:   Minor Injury

Window Size	Function	Remarks
Small	$Pr = \exp(1.1995+0.002531*A^{1.5}-8.773/A^{2})$ $Pr = \exp(1.273+0.0004148*B-15.492/B)$	Pressure Range Impuls Range
Medium	$Pr = \exp(1.3791+0.0004512*A^{2}-2.6251/A^{1.5})$ $Pr = \exp(1.317+0.0005657*B-6.550/B)$	Pressure Range Impuls Range
Large	$Pr = \exp(1.3942+0.0007816*A^{2}-1.155/A^{1.5})$ $Pr = \exp(1.337+0.0008585*B-2.688/B)$	Pressure Range Impuls Range

Table A-3:   Severe Injury

Window Size	Funktion	Remarks
Small	$Pr = \exp(0.9597+0.001226*A^{1.5}-11.630/A^2)$ $Pr = \exp(1.024+0.0001758*B-19.844/B)$	Pressure Range Impuls Range
Medium	$Pr = \exp(1.1023+0.0001550*A^2-3.1628/A^{1.5})$ $Pr = \exp(1.044+0.0002281*B-8.121/B)$	Pressure Range Impuls Range
Large	$Pr = \exp(1.1076+0.0002735*A^2-1.374/A^{1.5})$ $Pr = \exp(1.053+0.0003526*B-3.279/B)$	Pressure Range Impuls Range

Table A-4: Lethality

Remark:

$$Pr = \exp(.....) = e^{(.....)}$$